The Design of a Cable Driven Variable Stiffness Three Fingered Robotic Hand via Layer Jamming

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Ishan Singh Mann

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Defense Committee:

Haijun Su, Ph.D. (Advisor)

Dr. David Hoelzle

ABSTRACT

Soft robotics is an important milestone in the field of robotics research. Due to high compliance of soft robots, they can be extremely durable, less likely to cause damage to the surrounding environment, and hence much safer for use around humans. However, there are some limitations with highly compliant soft robots. The inherent flexibility of a soft robot makes it difficult to know the exact position of soft robot's end effector, which compromises positional accuracy of soft robots. Also, high loads and quick acceleration cause a soft robot to flex, which limits the potential uses of soft robots over traditional robots. Previous research has shown that a variable-stiffness robotic link can prevent the link from getting flexed when carrying high loads or during quick accelerations and deaccelerations by changing its stiffness. The purpose of this study is to make a variable stiffness three fingered robotic hand to demonstrate the benefits of variable stiffness. To do this, different variable stiffness technologies and actuation methods were studied, and layer jamming was selected as the variable stiffness technology with cables as an actuation method. A three-fingered robotic hand was designed which could be actuated by cables and change its stiffness by layer jamming. The designed robotic hand was tested by lifting different objects and the maximum load carrying capacity of the hand was determined to be 9 times more when using variable stiffness. The developed soft robotic hand which can vary its stiffness shows the potential to overcome the major limitations of soft robots and expand the areas where soft robots can be potentially used over traditional robots to promote a safe workplace environment which involves human-robot interaction.

ACKNOWLEDGMENTS

I would like to thank Dr. Haijun Su for giving me the opportunity to work on this very interesting project. Dr. Su guided me constantly through the project and gave helpful feedback at every step, without which I would not have been able to complete this project. I would also like to thank him for allowing me to use the facilities at DISL.

I would also like to thank graduate student Xianpai Zeng for helping me in designing the robotic hand, making me familiar with layer jamming and helping in the testing of the hand. I would also like to thank him for making me familiar to the facilities at DISL.

I would also like to thank John Ouyang, who helped me in getting the test setups ready and helped in creating sealed bags for layer jamming to work.

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CHAPTER 1: INTRODUCTION

1.1 Soft Robots

Soft robotics is an important milestone in the field of robotics research. Soft robots are usually made from highly-compliant materials and due to their highly compliant nature and theoretically an infinite degree of freedom, soft robots are extremely durable, less likely to damage fragile payloads or harm humans, and more dexterous [1][2]. Soft robots are relatively safe where human machine interaction is involved and they have the potential to exhibit unprecedented adaptability [1]. Soft robots can also be less expensive, lighter in weight, and easier to customize for different applications when compared to traditional robots [3]. Despite the advantages of soft robots over traditional robots, there are some limitations with highly compliant soft robots. They cannot carry heavy load as compared to their traditional counterpart due to their continuously deforming structure. Additionally, quick accelerations and jerks cause the soft robotic link to bend in the motion. Another challenge with soft robots is to maintain a high positional accuracy because their inherent flexibility makes it difficult to know the exact position of the soft robot's end effector [4]. These drawbacks limit the potential uses of soft robots.

1.2 Variable Stiffness Advantages

The major limitations of a soft robot can be overcome by having a robot that can vary its stiffness. Robots which can vary its stiffness can use the benefits of soft robots while maintaining the performance characteristics of traditional robots. For instance, a robot can become stiff when high positional accuracy or high load carrying capacity is required and it can become less stiff and compliant to prevent injuring people or destroying objects in its environment. Existing research also shows that robotic arms designed with greater compliance are less likely to cause injury to humans [5][6]. The fact that a variable stiffness robot can combine the advantages of both soft and traditional robots while leaving out their limitations has led to the topic being vastly studied and researched on.

1.3 Thesis Objective

The purpose of this thesis is to design and make a working prototype of a variable stiffness three fingered robotic hand which combines the benefits of both soft and traditional robots. The variable stiffness robotic hand developed will be then used to lift specified objects. This thesis aims on finalizing an accurate actuation mechanism for the fingers of the robotic hand to move from relaxed position to grasping position and then incorporating a variable stiffness technology in the design to hold the grasping position with enough force to lift the specified object. The main objective of the thesis is the demonstration of a variable stiffness robotic hand which combines the benefit of traditional and soft robots.

1.4 Overview of Thesis

The thesis is composed of six chapters. Chapter 1 discusses the advantages and limitations of soft robots, the advantages of variable stiffness technologies, the objective of the thesis and the overview of thesis. Chapter two consists of the conceptual design which included the different variable stiffness technologies and actuation methods that were studied and selected for the robotic hand. Chapter three consists of concept verification for the chosen actuation and the variable stiffness method. Chapter four consists of the design process of the robotic hand which included three iterations and finalizing the electronics. Chapter five included prototyping and the different tests that were performed on the robotic hand. Chapter six includes the summary and potential future work.

CHAPTER 2: CONCEPTUAL DESIGN

This chapter includes the different types of actuation methods and variable stiffness technologies considered and an in-depth discussion of finalizing the concepts to actuate and vary the stiffness of the fingers of the robotic hand.

2.1 Variable Stiffness Technologies

(a) Linkage mechanism to vary the stiffness.

Various stiffness control technologies have been studied in the past. Design Innovation and Simulation Laboratory made a variable stiffness robotic link with active stiffness control. The robotic link consists of two parallel beams and the stiffness of the beams can be controlled by changing the shape of the beams. Figure 1 shows the different beam positions and the corresponding stiffness.

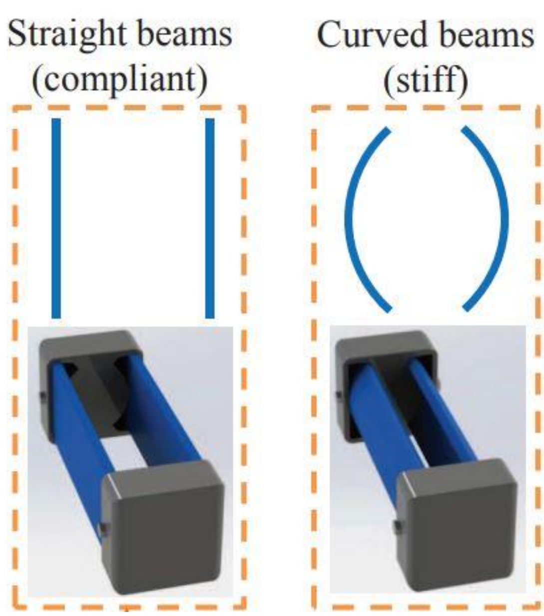


Figure 1: Variable stiffness robotic link with parallel beams [6]

The curvature of the two parallel beams can be controlled by using a mechanical linkage mechanism. Figure 2 shows the two extreme positions of the mechanical linkage to make the beams compliant and stiff.

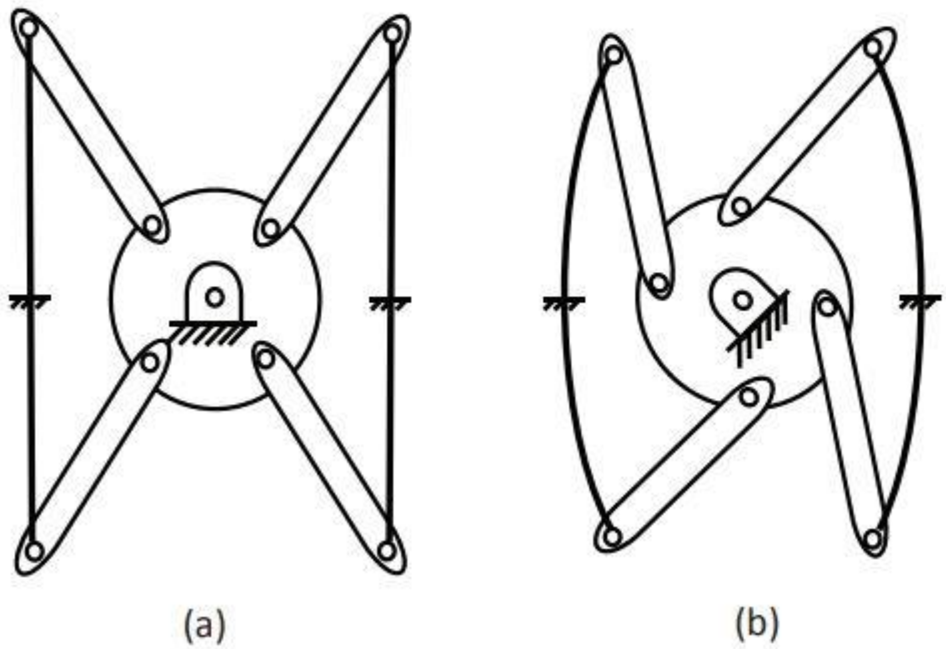


Figure 2: (a) The linkage mechanism at the flat beam shape.
(b) The linkage mechanism at the curved beam shape [6]

This design allows for a 3.6 times stiffness change [6]. However, this method uses a linkage mechanism to change the stiffness, which requires linkages, motors to actuate the linkage and other components which make the design very complex for a finger. Furthermore, given the size of the robotic hand being designed is in the vicinity of the size of an actual human hand, it was not possible to add three linkage mechanisms and their actuators in the given space. Hence this method was not used to vary the stiffness of the fingers of the robotic hand.

(b) Low melting point alloy to vary the stiffness

Another method to vary the stiffness which does not use a mechanical system and additional actuators is using a low melting point material inside the link. Low melting point materials can be either polymers or alloys, however, alloys are usually preferred because the heating of polymers is usually slower due to their low thermal conductivity [7]. The configuration of a variable stiffness robotic link is embedding a low melting point alloy in a capsulated layer which can be made of a soft material like silicon. When current is passed through the alloy, it leads to the alloy being heated up and it melts. When the alloy melts, it changes from solid state to a liquid state and hence the stiffness of the structure decreases. Such a configuration is capable of changing the stiffness by 25 times [7]. Although the stiffness change is high, this method does not allow active stiffness control since it takes time to melt the alloy and it takes even more time for the alloy to cool down to make the structure stiff again. Another drawback of this method is that low melting point alloys are susceptible to fracture at low strain amounts [7] and hence not durable enough to handle heavy loads and high impacts. Hence this method to vary the stiffness was rejected for the robotic hand.

(c) Magnetorheological elastomer to vary stiffness

Magnetorheological elastomers are solids with embedded micro or nano sized ferromagnetic particles. As a result, the mechanical properties of these materials can be controlled by the application of magnetic field. This technology has already been used to adjust the spring constant of vibration absorbers in real time [8]. The elastomers must be extremely flexible for the ferromagnetic particles to shift within it. The materials most commonly used are soft materials like silicon and hence they are not good for structural components. Furthermore, the electromagnets pose a packing difficulty for robots with moving parts. Thus, this method could not be used for varying the stiffness of the robotic hand.

(d) Layer jamming to vary stiffness

Jamming structures used to vary stiffness consists of a sealed volume filled with either a granular material or sheets of materials, when sheets are used, the technique is called layer jamming. A vacuum pump is used to create negative pressure inside the sealed volume and the negative pressure presses the sheets together increasing the friction between them. As a result of increased friction, it becomes harder for the particles to move relative to each other and hence it becomes stiff. The greater the vacuum pressure, the more the friction between the sheets and the stiffer the structure would be. Hence, the stiffness of the structure can be controlled by just varying the negative pressure which can be controlled by a vacuum pump. Robots using jamming structures have demonstrated many advantages of soft robots combined with the capabilities of traditional rigid robots, which is what is required for the robotic hand. Also, since the stiffness can be changed by just changing the pressure, it allows for active stiffness control. Therefore, layer jamming was finalized as a method to vary the stiffness of the robotic hand.

2.2 Actuation Method for Robotic Hand

(a) Shape memory alloy (SMA) for actuation

Shape memory alloys are alloys, which when heated to a critical temperature return to previously trained shapes via a phase transformation from Martensite to Austenite [10]. Hence shape memory alloys are often used as actuators. SMAs are usually embedded in the structures to be actuated as wires, coils or rectangular cross sections. An example of a SMA is a Ni-Ti alloy. An SMA strip can return fully to its original shape when no resistance is applied [10]. Figure 3 shows the actuation and the shape recovery cycle of an SMA actuator in its initial position, grasping position and relaxing position.

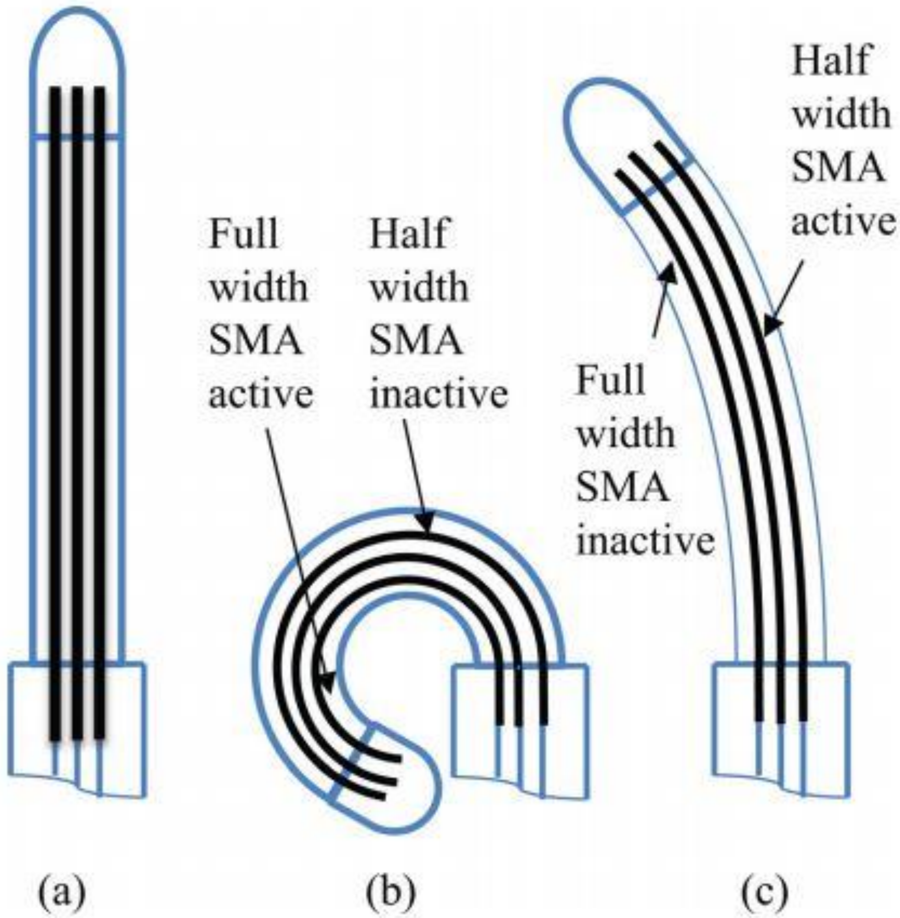


Figure 3: The actuation and shape recovery cycle of SMA actuator in its (a) initial position (b) grasping position (c) releasing position [10]

Current can be passed, and resistance wires can be used for actuating SMAs. It is a very effective method to actuate the robotic hand. However, the only limitation of this method is that it is not instantaneous. It takes about 10-30 seconds for the finger to completely bend [10] and it also takes time for the finger to return to its original shape. A robotic hand would lose its purpose if the actuation process is not instantaneous and hence SMAs were rejected as an actuation method.

(b) Pneumatic actuation

Pneumatic actuation is the use of compressed air for actuation. Previous research in the field of soft robotics have demonstrated that using compressed air to inflate and deflate desired parts of a soft robot can lead to desired movements of the soft robot. An example of such a soft robot can be seen in figure 4 where different sections of a soft robot are actuated at different instances of time to move the soft robot.

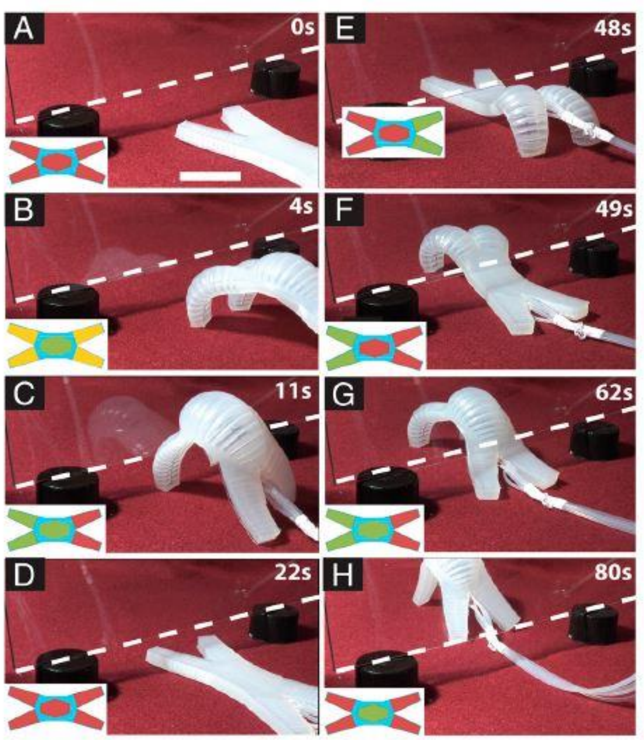


Figure 4:Pneumatically actuating different sections of a soft robot to create movement [11]

Another option to pneumatically actuate the fingers of the robotic hand is the use of air muscles. An air muscle is a soft material which can be expanded or contracted with the use of compressed air. An example of such a muscle can be seen in figure 5.

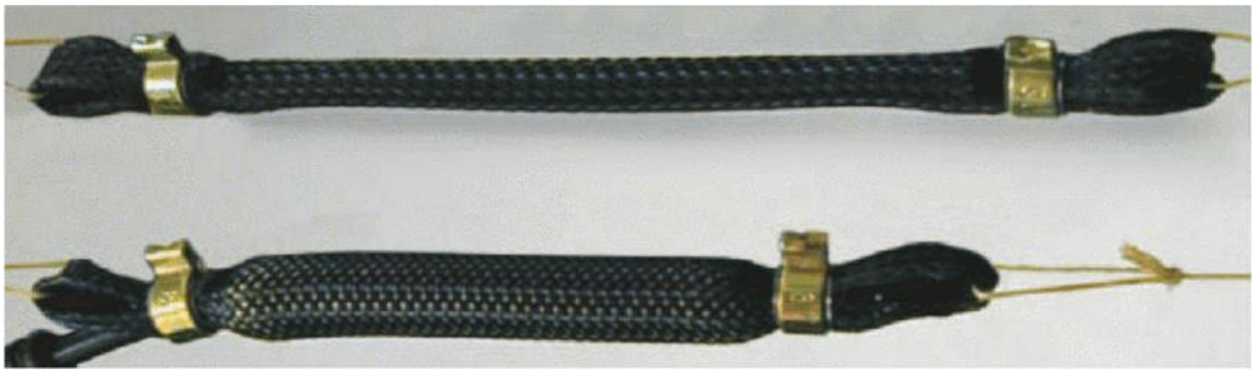


Figure 5: Air muscle in its relaxed and contracted shape [12]

However, the use of pneumatic actuation would require several valves if different parts of the fingers had to be actuated to make it bend and relax. On the other hand, air muscles would require less number of valves, but it is not feasible to make such a small air muscle that can fit inside the size of a human finger and not affect its stiffness. As a result, pneumatic actuation, which is although a very effective way for actuation could not be used because of size constraints.

(c) Cables for Actuation

Using cables for actuation of robots is one of the easiest and the most common ways to actuate a robotic link. This is because of the simplicity of the design. A cable is usually passed through the structure from one end to the other and when the cable is pulled, the robotic link bends in the direction perpendicular to the cable. Figure 6 shows a general cross section view of a cable driven robotic link.

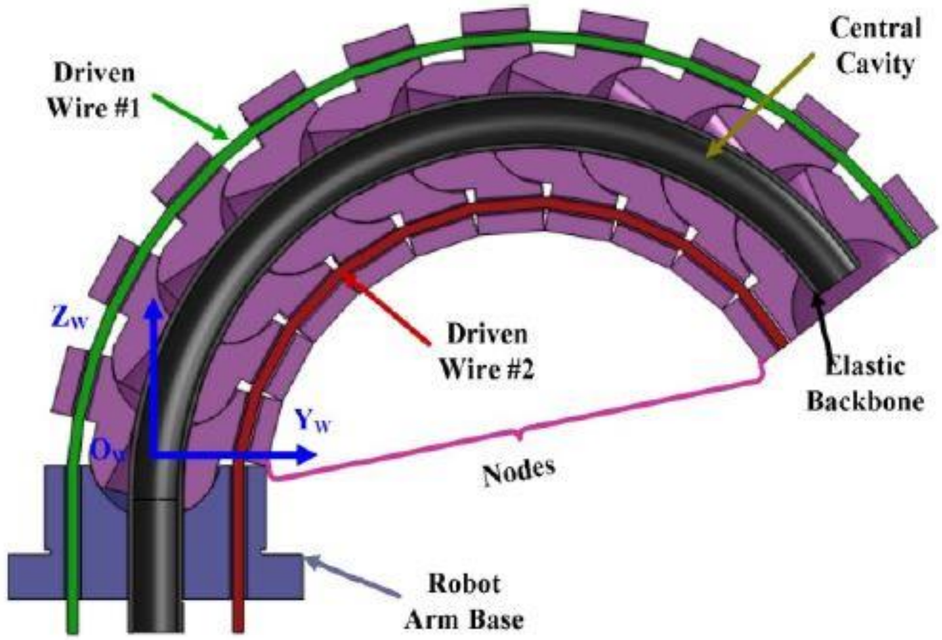


Figure 6: Cross section view of a general cable driven robotic link [13]

The soft robotic link driven by cable is generally consisted of multiple segments called nodes or cells and the space between these nodes or cells serves as a joint. Figure 7 shows the illustration of bending of joints.

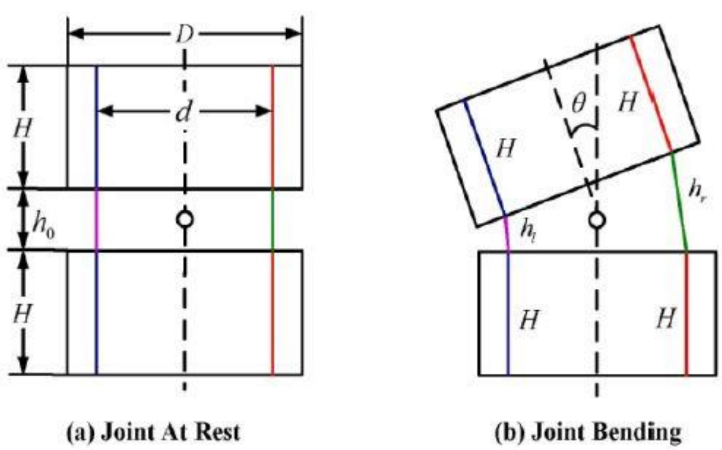


Figure 7: Illustration of Joint bending in a cable driven robotic link [13]

This method is also very effective for precision control because the relation between the required bend angle and the length of wire to be pulled/retracted can be found by simple geometry. Due to the simplicity of design as well as the ability to precisely control the bend angle of the finger, this method was chosen as the actuation method.

CHAPTER 3: CONCEPT VERIFICATION

This chapter consists of the verification of the conceptual design to actuate the fingers using cables and changing the stiffness using layer jamming.

3.1 Cables for Actuation

There are several cables available with each of them having different properties. The properties of the cable that would make it ideal to actuate the finger are as follows:

- The cable should be non-stretchable. This is to ensure the precision of the end effector. A non-stretchable cable will allow the finger to bend by a certain degree every time the cable is pulled by a fixed amount. However, on the other hand, a stretchable cable will bend by some different degrees each time even if the cable is pulled by a fixed amount.
- The cable should be highly flexible. Since the finger has to bend and the cable is passed through the finger, the cable should be flexible enough so that it bends with the finger without adding a significant resistance to the bending.
- The cable should not be able to bend permanently. If the cable bends permanently, not only will it add to the resistance in bending the finger, it will also prevent the finger from bending if it does not come back to its original shape after it is let gone off.

Based on the above cable properties, ultra-flexible-non-stretchable coated steel wire was finalized to actuate the finger mechanism. A scaled-up version of the flexible finger was 3D printed with holes in it and the ultra-flexible non-stretchable coated steel wire was passed through it. The ends of the steel wire were held together with cable connectors on both the sides, which uses set screws to hold the cables together. The picture of the finger beam with end connectors can be seen in figure 8.

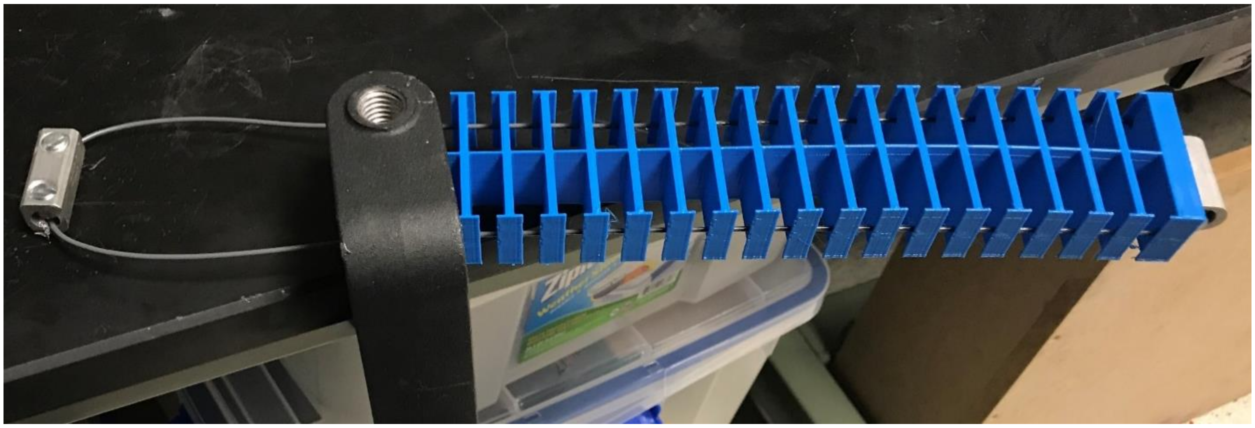


Figure 8: A 3D Printed finger beams with steel wires passing through and end connectors to secure the steel wire.

A hole was drilled through one of the end connectors and it was attached to a servo motor as seen in figure 9.

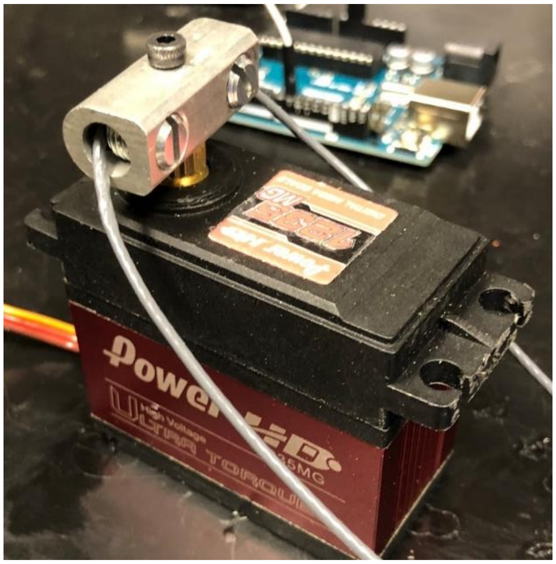


Figure 9: One of the end connectors connected to the servo motor

The servo motor was programmed to rotate 90° left and right. As a result, it would pull the steel wire and actuate the finger beam to bend. Figure 10 shows the finger beam bending towards left and right as the servo motor rotates.

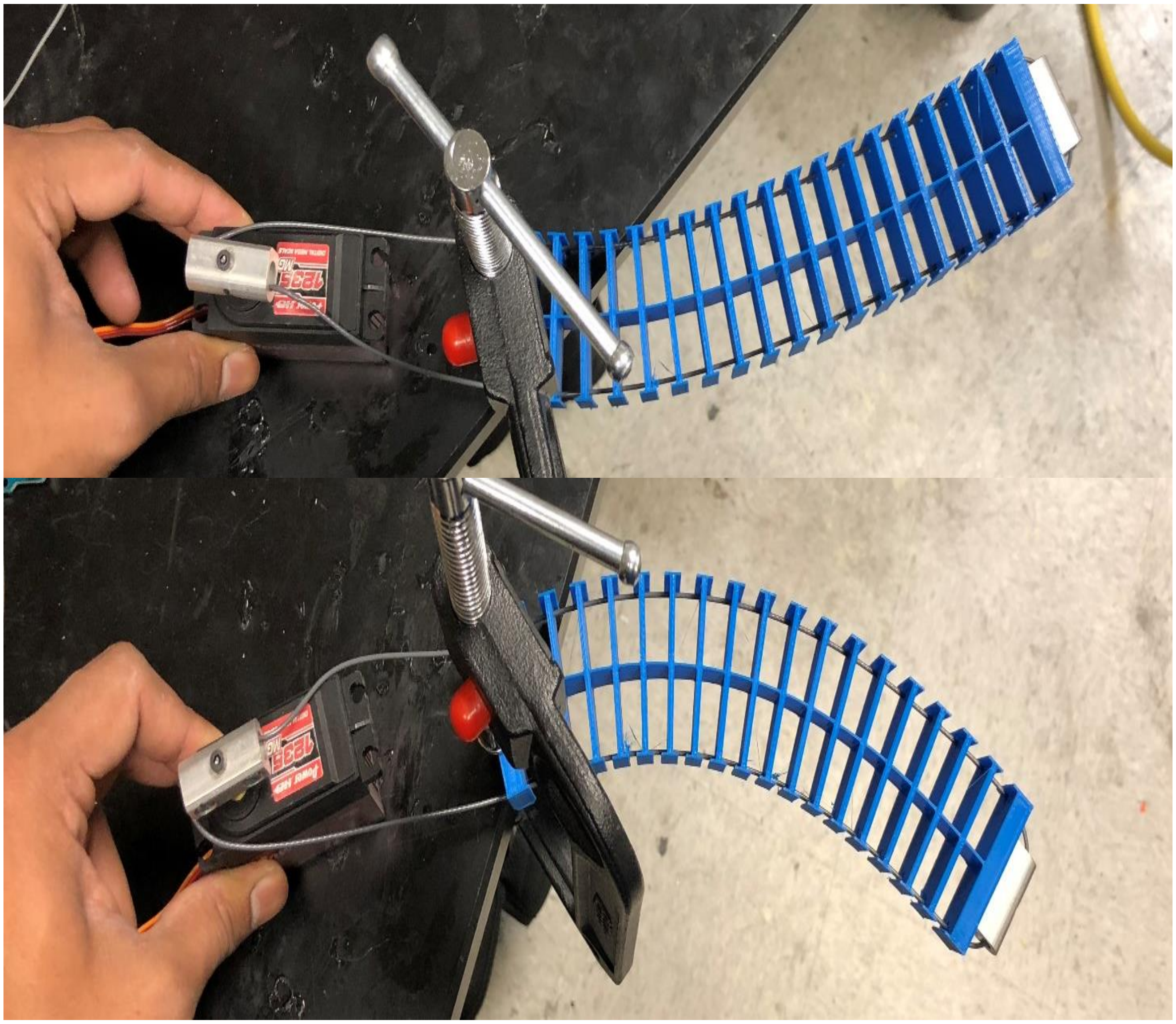


Figure 10: Finger beam rotates left and tight as the Servo motor roates by 90 °

Although steel wire was able to actuate the finger to bend, there were two limitations of the wire. The first is that the width of the actual finger beam is 12 mm and the smallest diameter in which the steel wire is available is 5 mm. Since two wires are needed to actuate the finger, it adds up to

10 mm width of just the wires inside the finger. Hence the fingers will not be able to bend since the wires will take all the empty space inside the finger and will act as a rigid structure and hence resisting the finger to bend. Another limitation of steel wire was that the end connectors used move when the finger bend as shown in figure 11. The moving end effector inside the sealed volume can lead to tears in the vacuum bag and hence interfere with layer jamming. As a result, steel wire was not used as the actuating cable.

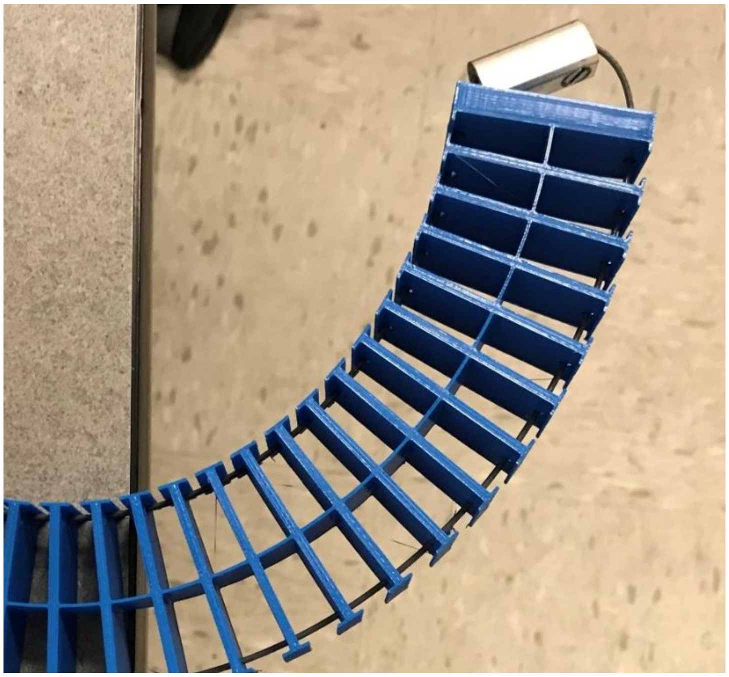


Figure 11: Moving end connector, which might pose a problem for the vacuum bag

Due to the limitations of the steel wire, an alternate cable which had all the required properties was selected. The selected cable was Trilene fishing cable. Apart from satisfying the required properties, fishing cable was selected because it is available in diameter as small as 0.7 mm. Another reason for selecting fishing cable was that it did not require end connectors to hold the cables at the end. A knot could be tied at the end of the cable, or the cable could be heated to form a burnt knot which would hold it in place. Figure 12 shows fishing cable inside the finger beam with the different securing methods.

Figure 12: Securing methods for fishing cable

3.2 Layer Jamming for Variable Stiffness

Past researchers at Design Innovation and Simulation laboratory (DISL) have already tested layer jamming technology. It has shown a stiffness change of up to 15.8 times using the setup shown in figure 13 [4]. Ongoing research at DISL has refined the setup to get a stiffness change as high as 80 times. Since layer jamming is a tried, tested and a verified method for variable stiffness at DISL, it was not tested as a concept. However, different materials were considered for making sealed bags and stiffness ratios of the considered materials were tested, which are discussed further in chapter 5.

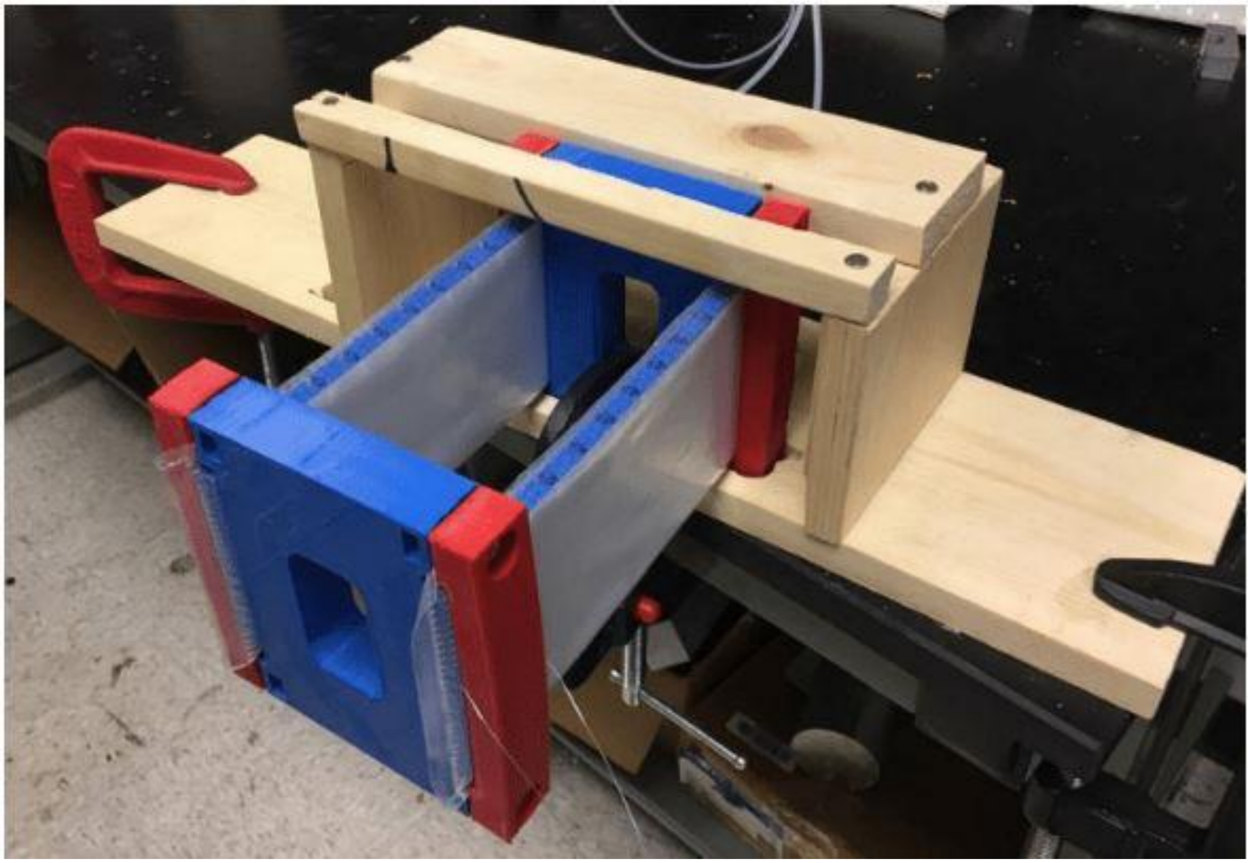


Figure 13: Layer Jamming setup at DISL which resulted in a 15.8 times stiffness change [4]

CHAPTER 4: DESIGN OF ROBOTIC HAND

This chapter consists of the design of the robotic hand. It covers 3 design iterations, the design process, the selection of electronics and fabrication of the robotic hand.

4.1 Iteration 1

The first design used a 3D printed circular ring with plates on the inside. The servo motors which would actuate the finger beam and the finger beams were attached to the plates on the inside of the circular ring using 3D printed brackets which would be fastened using M2 nuts and bolts. Figure 14 shows the Solidworks model of the first design iteration. The green colored part is the circular ring, the red colored parts are the brackets used to hold servo motors and the finger beams and the yellow colored parts are the finger beams.

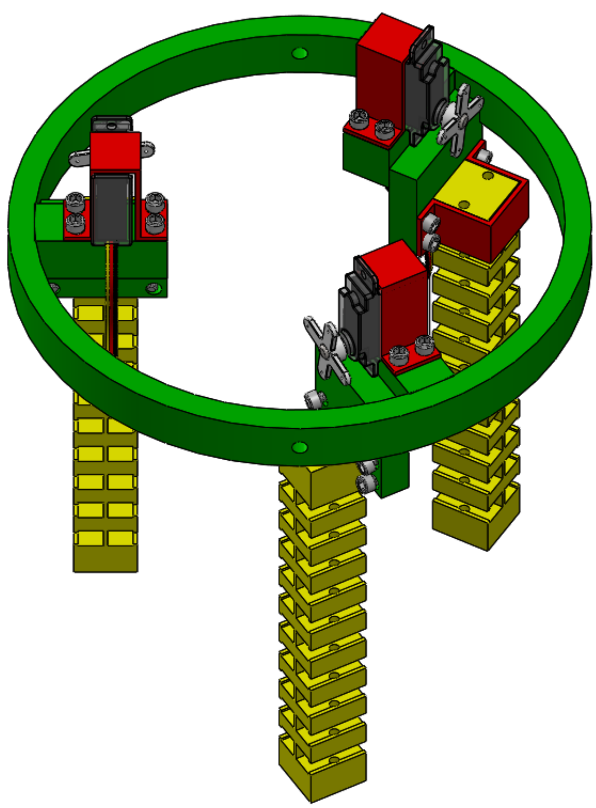


Figure 14: Solidworks model of iteration 1

This design was not selected because of two major limitations. The first is that nuts and bolts is not a reliable method to secure 3D printed parts. This is because the 3D printer material used was PLC, which is brittle and hence if the nuts and bolts were tightened very hard, it would lead to cracks in structure. The second limitation was that layer jamming could not be incorporated into this design. This is because for layer jamming to work, the fingers had to be contained inside a sealed bag. However, if fingers were sealed inside a closed volume for this design, there would be cables coming out of the fingers to the servo motors which would move as the servo turns and it is not possible to seal a moving component and hence it would not be possible to use layer jamming. Thus, a more viable design was explored which would not use nuts and bolts as a securing method and which would not have moving cables through a sealed volume.

4.2 Iteration 2

The second iteration of the design used a triangular base instead of a circular ring. The triangular base had hollow extrusions coming out into which the finger beams could be glued into. At the bottom of each hollow extrusion, there was space for a servo motor which would again be glued to the base. This takes care of the layer jamming problem from iteration 1 since the moving cables are inside the extrusions now. For this design, the entire robotic hand could be covered inside a sealed volume for the layer jamming to work. Figure 15 shows the Solidworks model of design iteration 2. The green part is the 3D printed triangular base and the yellow parts are the finger beams.

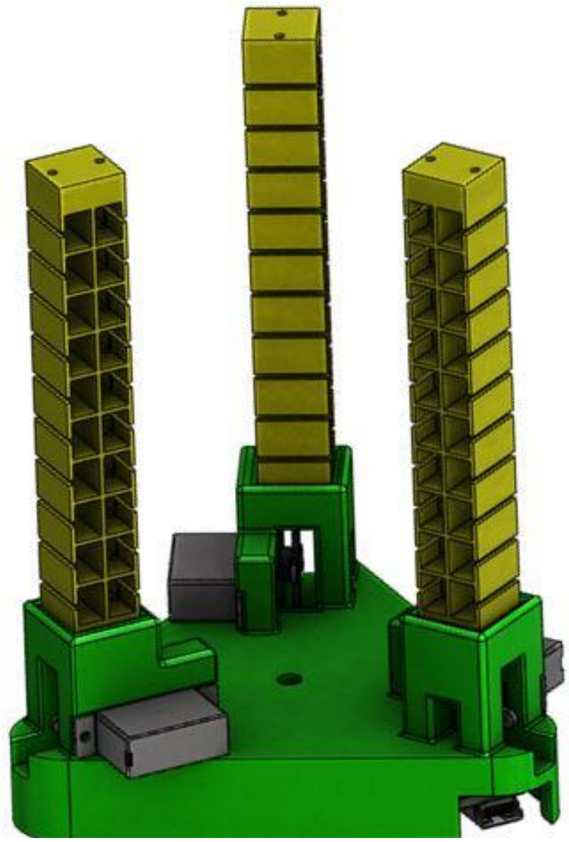


Figure 15: Solidworks model of iteration 2

However, this design was not selected because of two main reasons. The first is that the design uses glue to secure the finger beams and the servo motors, which is not a reliable fastening method. Also, it would be difficult to connect the cables running through the finger beam to the arm of the servo motor since the servo motor arm is inside a closed extrusion. The second reason is that for layer jamming to work on this design, the entire robotic hand had to be covered inside the closed volume. This makes the robotic hand look very shabby and it makes all the parts dependent on each other because if the closed bags leaks, the entire structure fails. Hence, deign iteration 3 is a modified version of iteration 2, which makes the design more modular, in which the fingers are independent entities instead of an integrated design where all the parts are integrated.

4.3 Iteration 3

The third design iteration is the final design which is a modified version of the second iteration, which uses separate finger subassemblies to make the design more modular. This iteration of the design consists of three different finger subassemblies that are attached to the triangular base using 3D printed brackets. This design also uses metal inserts, which are heated and inserted inside 3D printed parts along with bolts to fasten other parts to them. For each finger subassembly, the finger beam is clamped inside the 3D printed parts and secured using inserts and M2 bolts. The servo motor goes below the clamps where the cables running through the finger beam are attached to the servo arm. After everything is assembled, a front cover is secured onto the finger subassembly. Figure 16 shows the exploded view of each finger subassembly. The yellow part is the finger beam, the green part serves as one half of the clamp as well as a place to mount the servo motor onto, the red part serves as the other part of the clamp and the light brown part is the front cover.

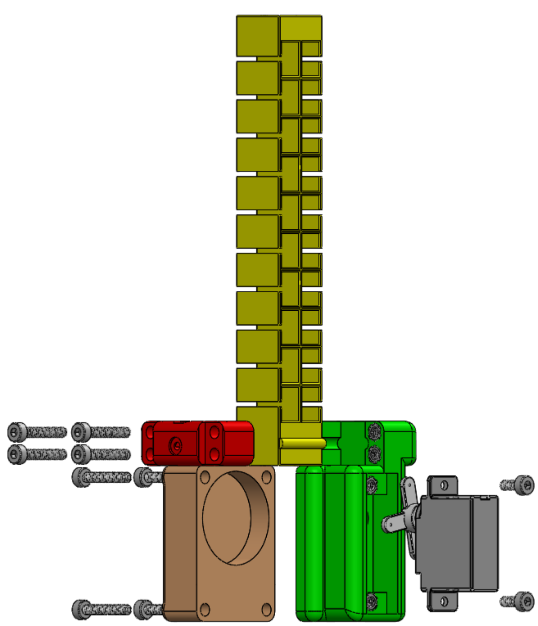


Figure 16: Exploded view of a finger subassembly

Figure 17 through 20 shows the step by step assembly of each finger subassembly.

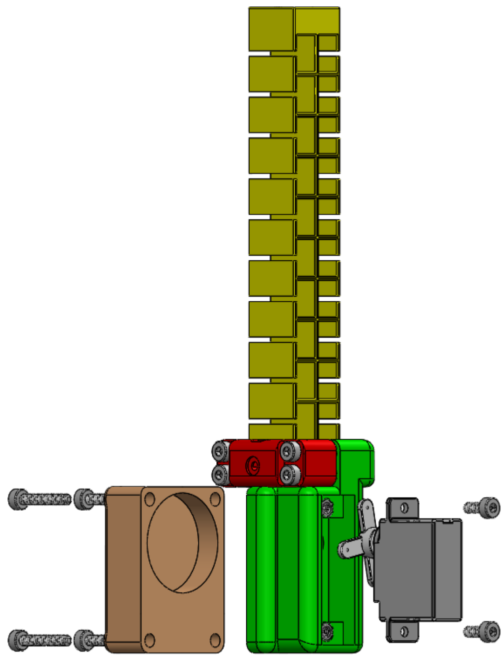


Figure 17: Finger beam clamped between red and green parts

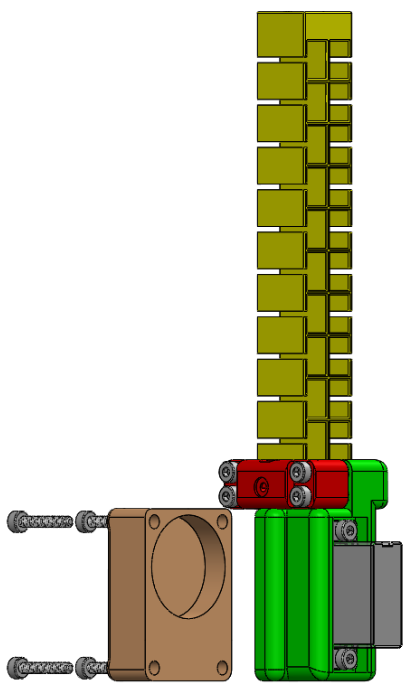


Figure 18: Servo motor attached to green part

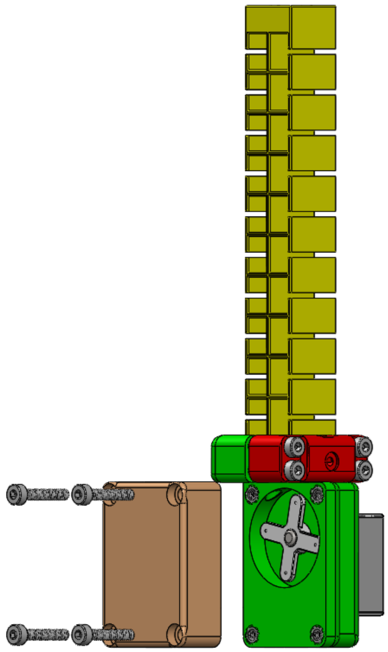


Figure 19: Brown front cover attached to cover the servo arm

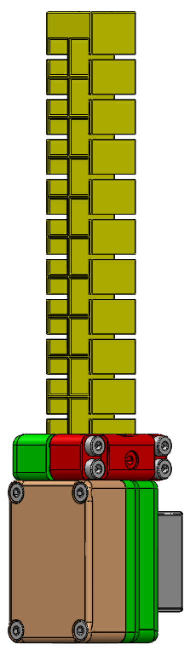


Figure 20: Finger sub assembly

The entire finger subassembly shown in figure 20 could be placed inside the closed bag and sealed. The three independent finger subassemblies could be attached to the base using a 3D printed bracket. Figure 21 and 22 shows the entire assembled robotic hand. The blue parts are the 3D printed brackets used to secure the finger subassemblies to the brown base. The groves in the brown base are for tubes which will be used to change pressure to vary the stiffness using layer jamming.

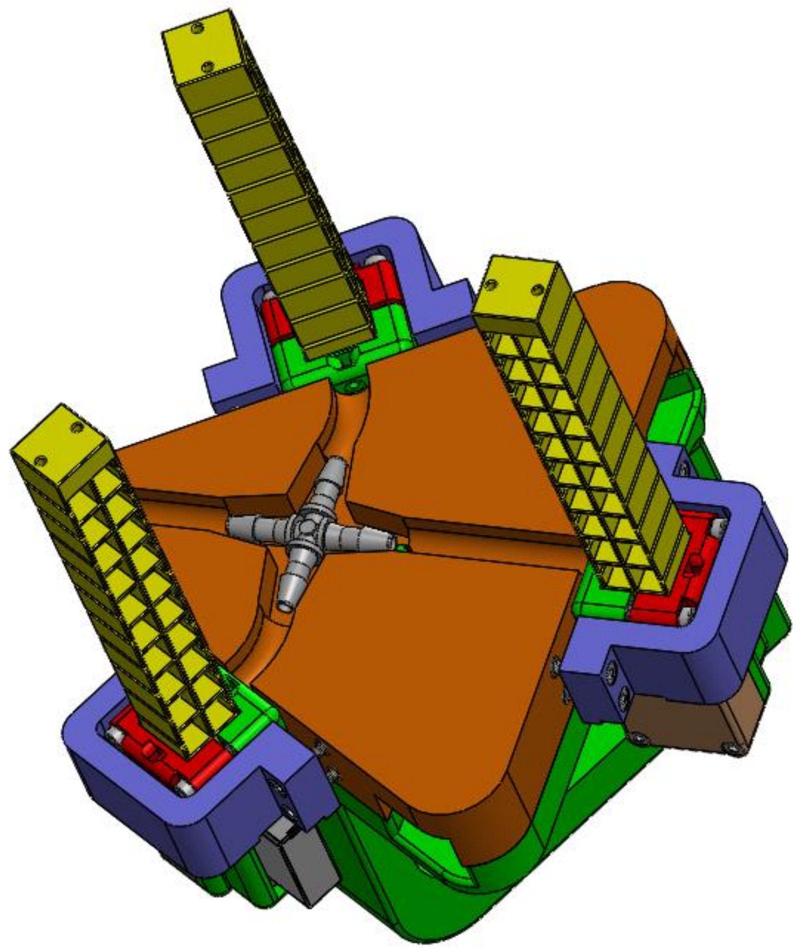


Figure 21: Solidworks model of the robotic hand

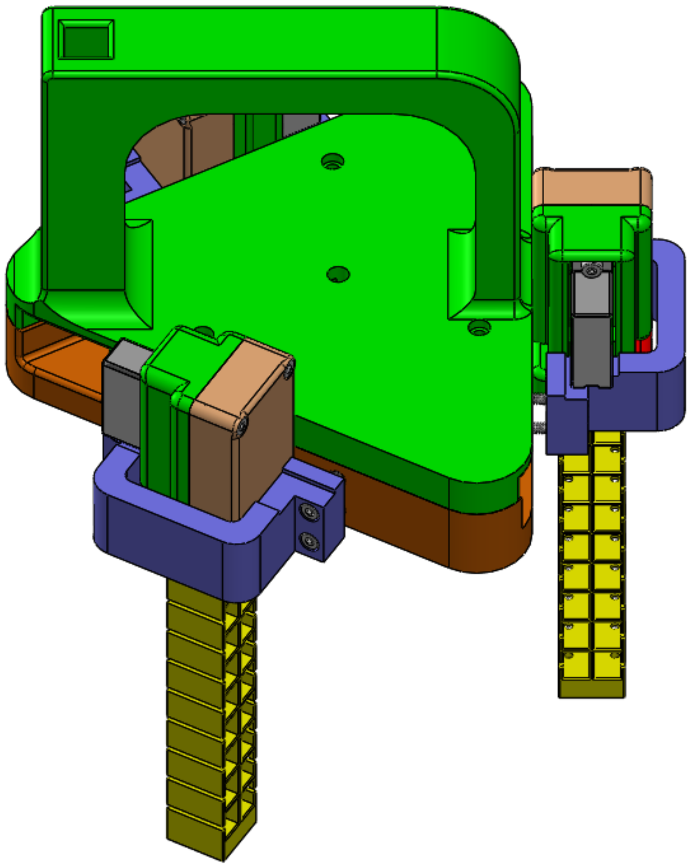


Figure 22: Solidworks model of the robotic hand

4.4 Electronics

The electronics used to actuate the fingers are servo motors, a micro controller, a power source and a battery charger. The servo motors used to actuate the fingers are Ultra Nano Hitec HS-35HD. The two primary reasons for selecting the particular servo are that it produces a torque of 11.0 oz/inch, which is enough to pull the cables and actuate the finger, and the size of the servo (18.6 mm X 7.6 mm X 15.5 mm) is ideal for incorporating it into the design of the robotic hand. Figure 23 shows the picture of the servo relative to the size of a human hand.

Figure 23: Size of the servo relative to a human hand

The battery used to power the servo motors is a 3.7 V Li-ion battery. However, a voltage regulator is also required since the operating voltage of the servo motors is 5 volts. In addition to the voltage regulator, a battery charger is required so that the battery can be charged instead of replacing the battery after every time it is dead. PowerBoost 1000C is used as a voltage regulator. It also serves as a battery charger. Figure 24 shows the picture of PowerBoost 1000C

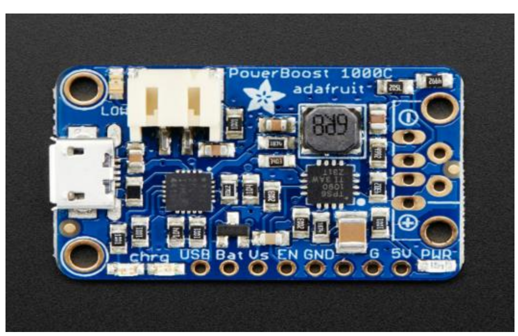


Figure 24: PowerBoost 1000C

The microcontroller used to control the movement of the servo motors is Arduino nano because it is very compact, cheap, has a high voltage input tolerance and user friendly. Figure 25 shows the picture of Arduino Nano.

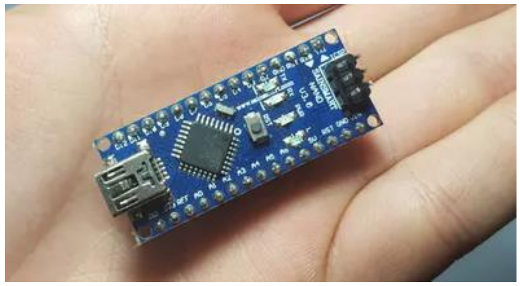


Figure 25: Arduino Nano

All the electronics were embedded in the base of the robotic hand. Figure 26 shows the Solidworks model of all the embedded electronics. The green part is the base, the red part is the Li-ion battery, the blue part is the voltage regulator and the battery charger, and the third part is Arduino nano.

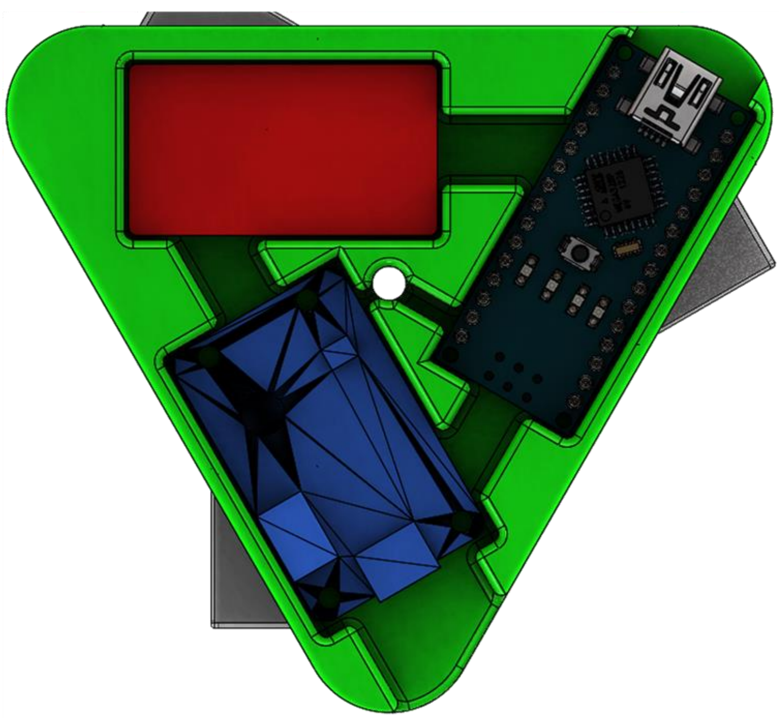


Figure 26: Embedded electronics in the base of robotic hand

Figure 27 shows the circuit diagram of the electronic setup. The red wires are the positive connections, the black wires are the negative connections and the yellow wires the signal connections for the servo motors. The green pins are the pins that are used, and the red pins are the pins that are not used.

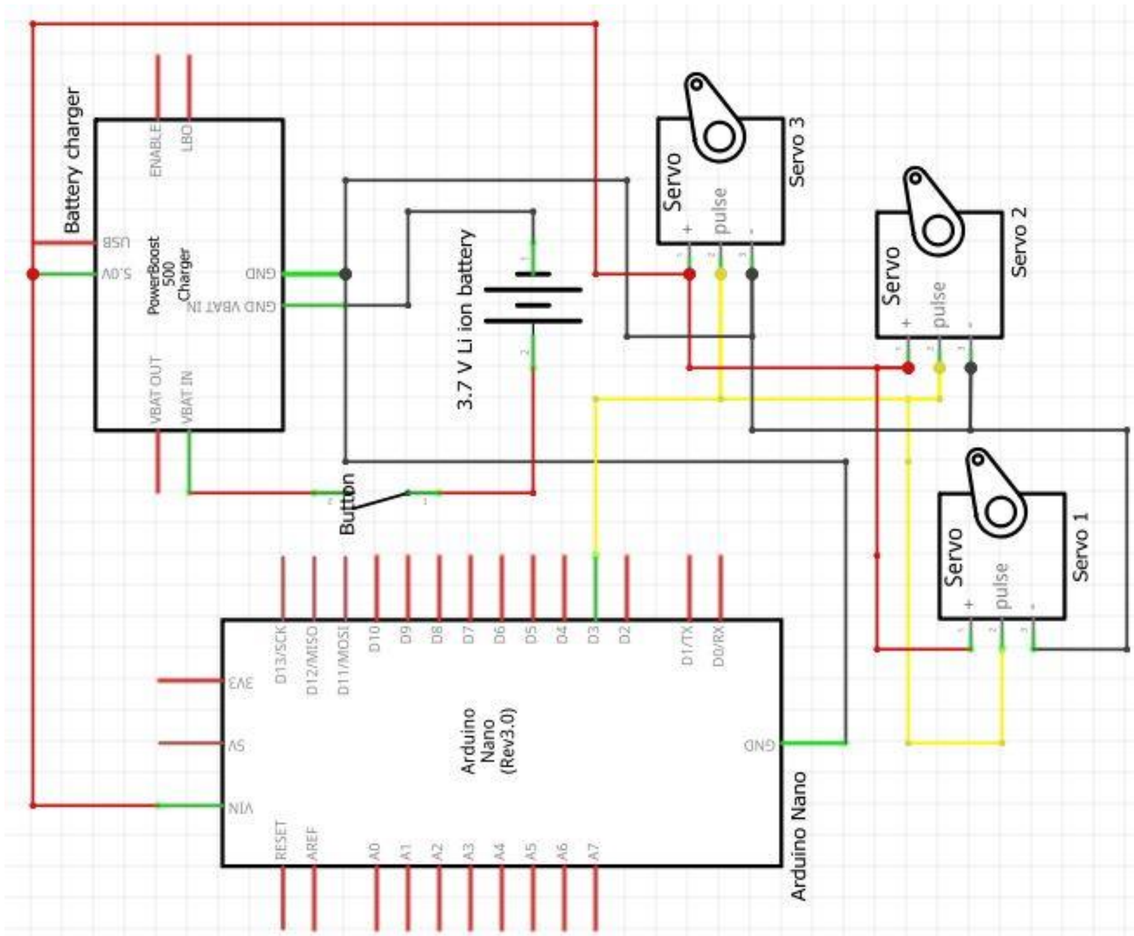
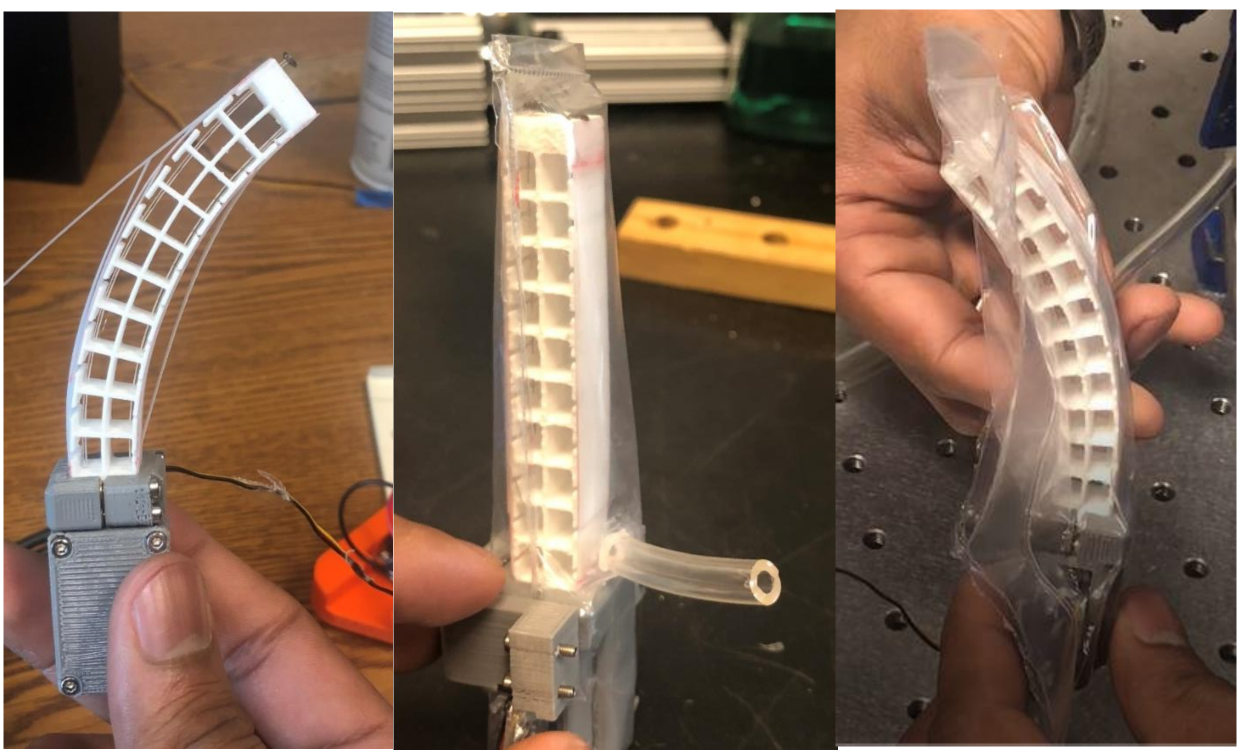


Figure 27: Circuit diagram of the electronic setup

CHAPTER 5: TESTING, PROTOTYPING DEMONSTRATION

This chapter consists of the methods and results of the stiffness tests that were conducted on the finger, prototyping, the maximum load test conducted on the hand and demonstrations of the robotic hand.

The parts of one finger subassembly were 3D printed and a finger was assembled with 4 layers on each side and stiffness testing was conducted on one finger. Figure 28 (a) shows a finger subassembly that has been actuated into the grasping position, figure 28 (b) shows the finger inside a sealed plastic bag and figure 28(c) shows the finger in the grasping position inside the sealed bag.



(a) (b) (c)

Figure 28: Finger assembly prototyping

5.1 Stiffness Testing

Stiffness testing was done on one finger to test the stiffness ratio at different pressures. Also, two different types of materials were tested to make the sealed bag. The materials tested were commercial vacuum bag and latex. Figure 29 shows the setup for stiffness testing. A finger assembly was sealed inside the bag and clamped at a fixed location. A force sensor was used to push the finger and the force data was recorded.

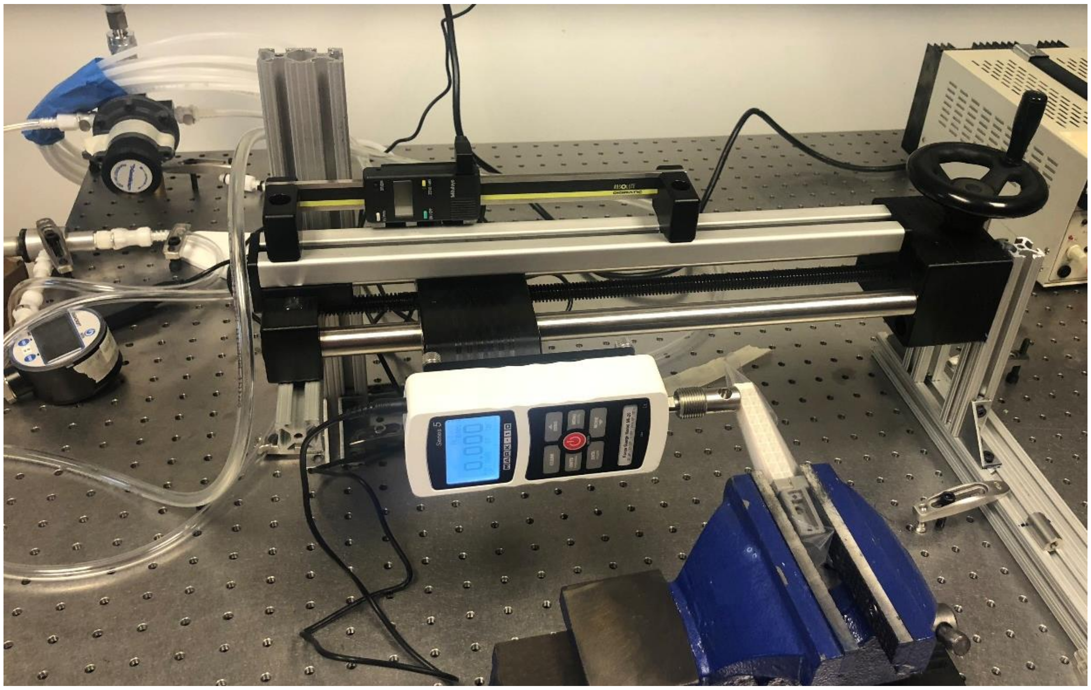


Figure 29: Stiffness testing setup

The tip of the finger was deflected 10 mm in increments of 0.25 mm and the corresponding force was recorded at each point. This was done at 0, 2.5, 5, 7.5, 10 and 12.5 psi. A plot was force v/s deflection plot was created and the data was fit to a linear curve. The slope of the line gave the stiffness at different pressure in N/mm. Figure 30 and 31 show the force v/s deflection plots at different pressures for commercial vacuum bag and latex respectively. Figure 32 and 33 show the stiffness ratios of commercial vacuum bag and latex respectively at different pressures.

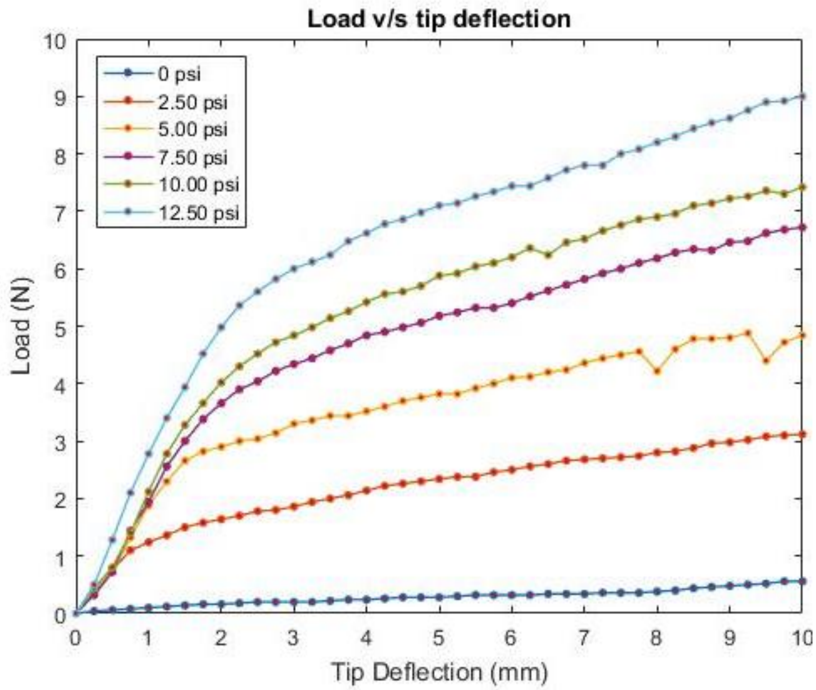


Figure 30: Load v/s deflection plot for commercial vacuum bag

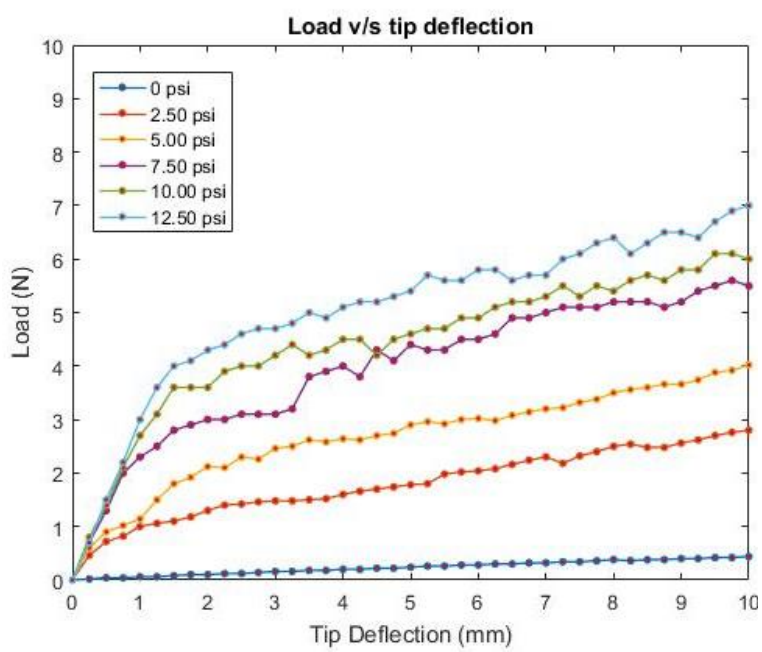


Figure 31: Load v/s deflection plot for latex bag

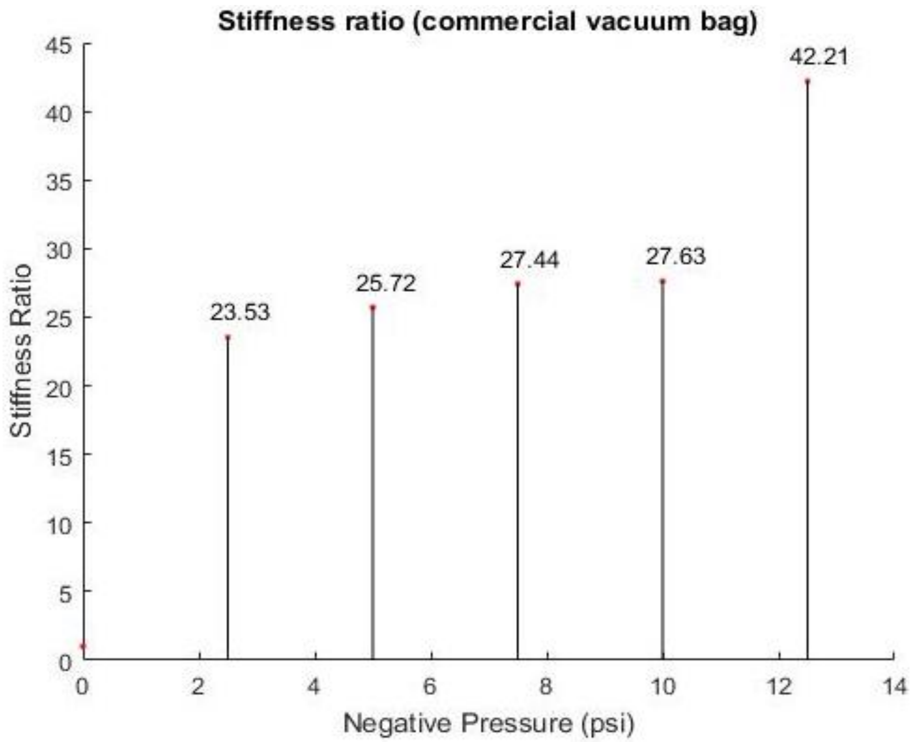


Figure 32: Stiffness ratio for commercial vacuum bag

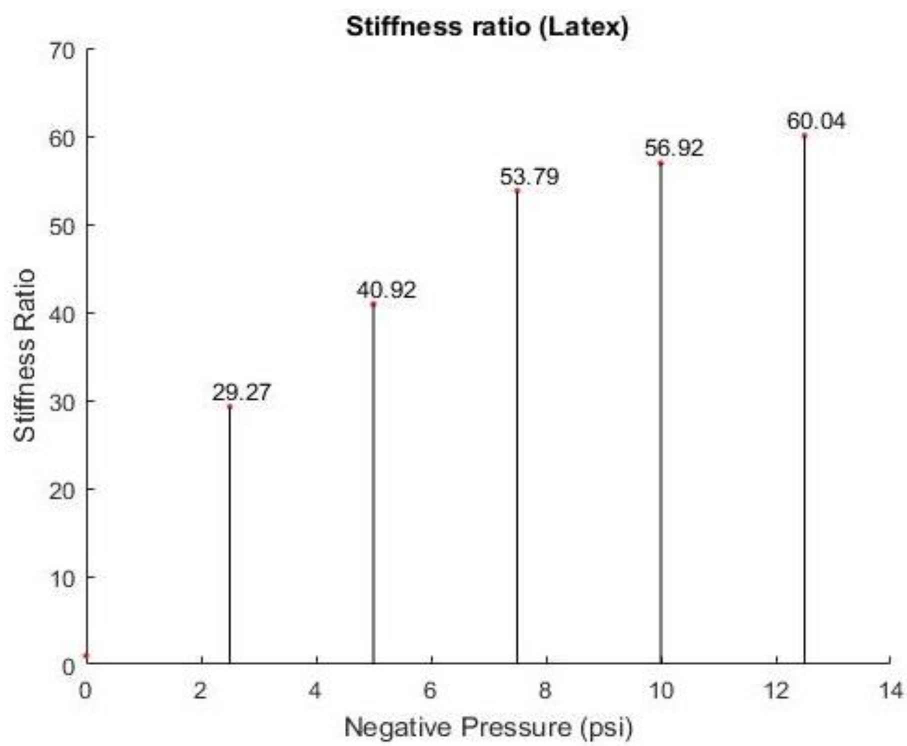


Figure 33: Stiffness ratio for latex bag

The results from stiffness test of both the materials are summarized in table 1.

Table 1: Stiffness ratios of commercial vacuum bag and latex

Negative Pressure (psi)	**Stiffness Ratio**	
	Commercial Vacuum Bag	**Latex**
0	1	1
2.5	23.53	29.27
5	25.72	40.92
7.5	27.44	53.79
10	27.63	56.92
12.5	42.21	60.04

The stiffness ratio for a sealed bag that is made of latex is higher than the stiffness ratio of a sealed volume made of commercial vacuum bag at all the pressures. At the highest pressure of 12.5 psi, the latex bag has a stiffness ratio of 60.04 and the commercial vacuum bag has a ratio of 42.21. Since the stiffness ratio of latex is more than the commercial vacuum bag, latex is used as the material to seal the finger subassemblies.

5.2 Prototyping

All the parts for the robotic hand were 3D printed from PLC. First, the parts for finger subassembly were printed and assembled with 4 layers on each side on each finger for layer jamming. Figure 34 and 35 shows the 3D printed parts and the assembled finger subassemblies. All the fingers were placed inside fingers in latex gloves which were cut to size and sealed using glue. The sealed fingers were attached to the 3D printed triangular base, on which the electronics were embedded to complete the robotic hand. Figure 36 shows the completely assembled robotic hand.

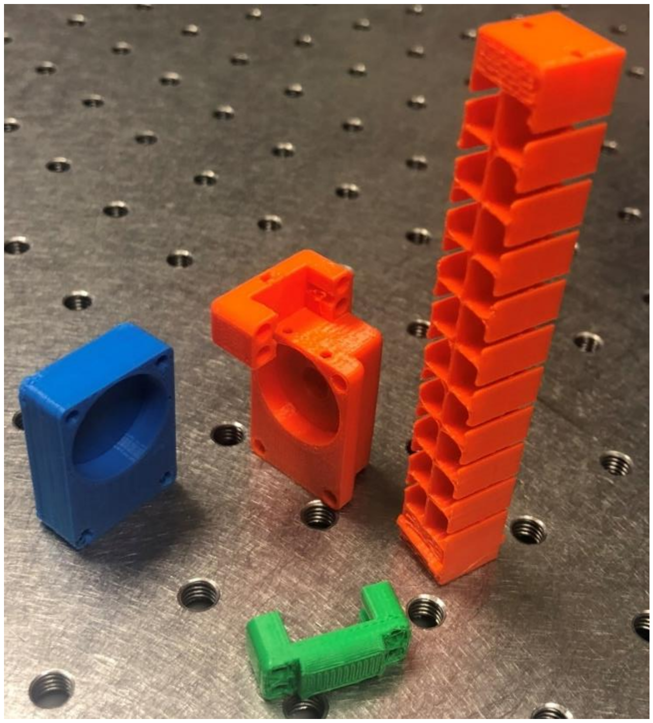


Figure 34: 3D printed parts for finger subassembly

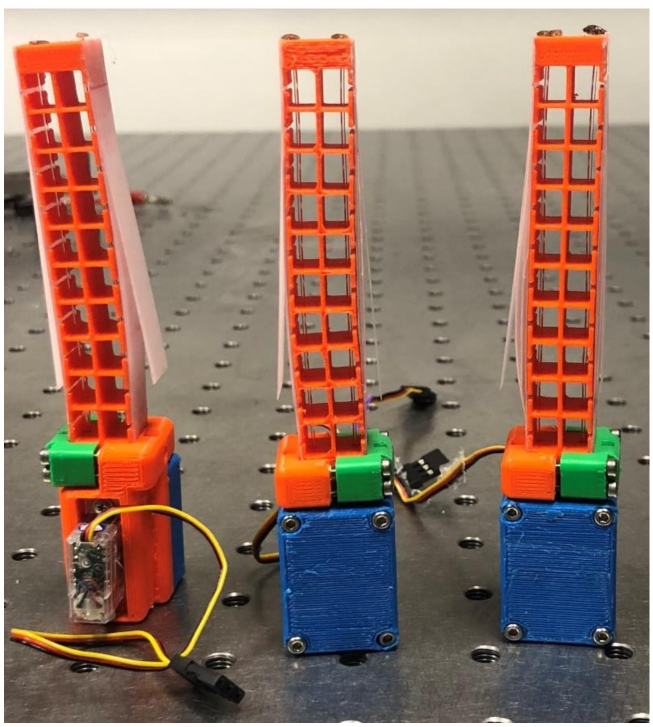


Figure 35: Assembled fingers

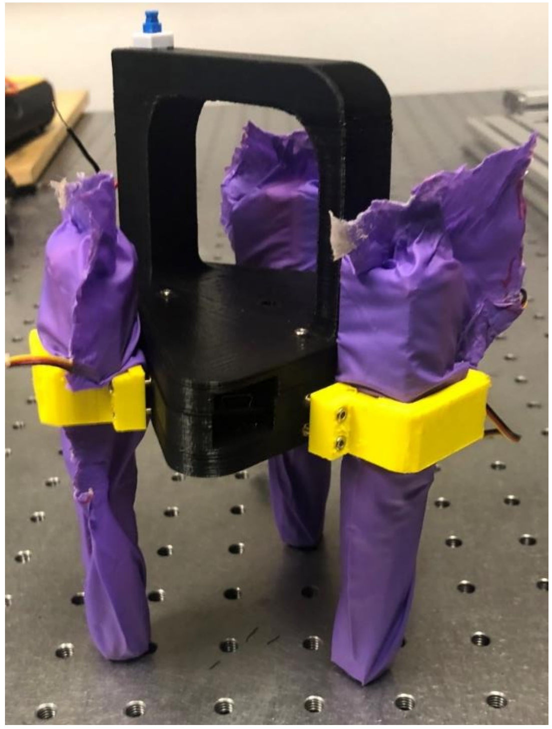


Figure 36: Robotic Hand

5.3 Maximum Load Test

The verification that the robotic hand works was done by grabbing and lifting different objects. Figure 37 shows the robotic hand lifting a tennis ball, aluminum t bar and an empty can.

Figure 37: Robotic hand lifting a tennis ball, aluminum t bar and empty can

After verifying the working of the robotic hand, a maximum load test was performed to know the maximum load it is capable of carrying with and without using layer jamming. For the maximum load test, the robotic hand was clamped horizontally with the help of a clamp and it was made to grab a tennis ball. A wire was drilled through the tennis ball which was attached to a force sensor. The force sensor was forced to move in the direction away from the robotic hand and the maximum force was recorded. A current reader was also used to read the maximum current drawn by the servos in the process. This test was done at a pressure of 0 psi (No layer jamming) and -12.5 psi (Maximum stiffness using layer jamming). Figure 38 shows the setup for the maximum load test.

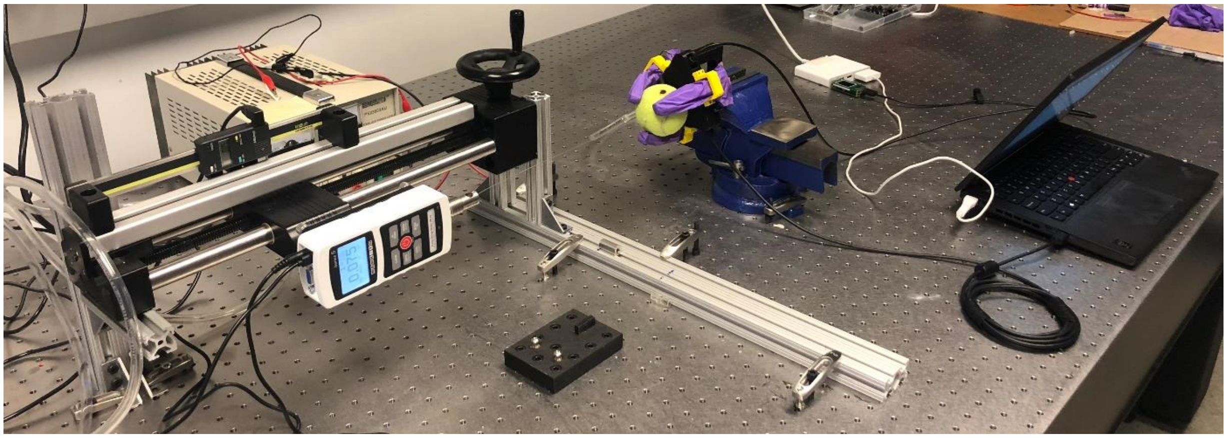


Figure 38: Setup for maximum load test

The results from the load test are summarized in table 2.

Table 2: Summary of maximum load test

Load Conditions	**Maximum Load (grams)**	**Current Consume (mA)**
Without Layer Jamming	150	800
Without Layer Jamming	1350	0

As it can be seen from the results, when layer jamming is used, the load carrying capacity of the robotic hand increases by 9 times. Also, the current consumption drops down to 0 mA because once vacuum is generated inside the sealed latex bags, the power is cut off and the robotic hand becomes stiff and holds its position. The validation of the measured results was done by trying to lift a calibrated 1 kg weight with and without layer jamming. The hand was not able to lift the 1 kg block without layer jamming, but it was able to lift it using layer jamming. Figure 39 and 40 show the pictures of the hand trying to lift the 1kg block without and with layer jamming respectively.

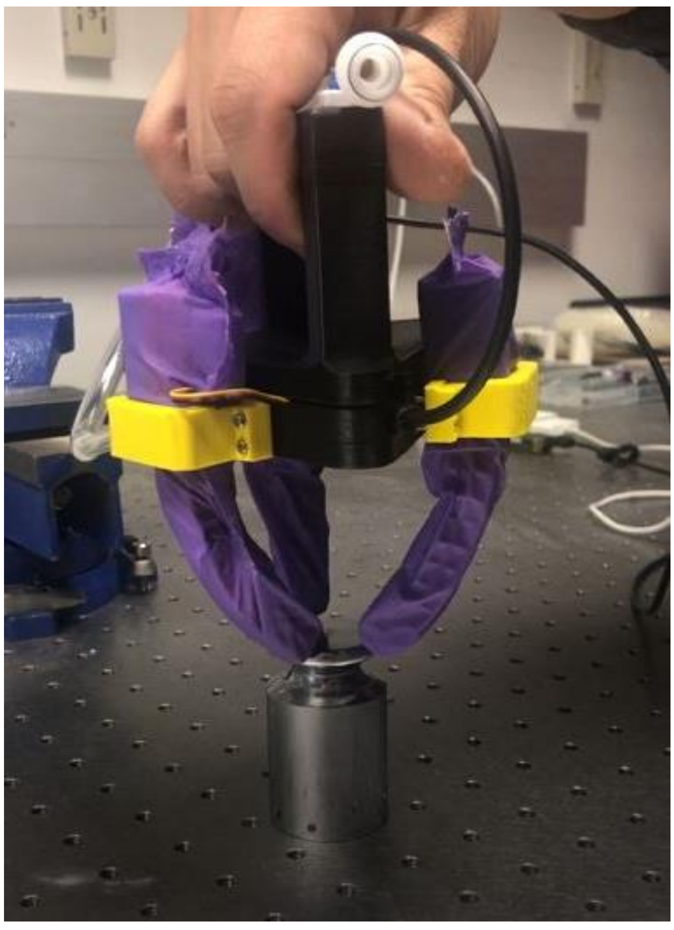


Figure 39: Unable to lift 1 kg block (No layer jamming)

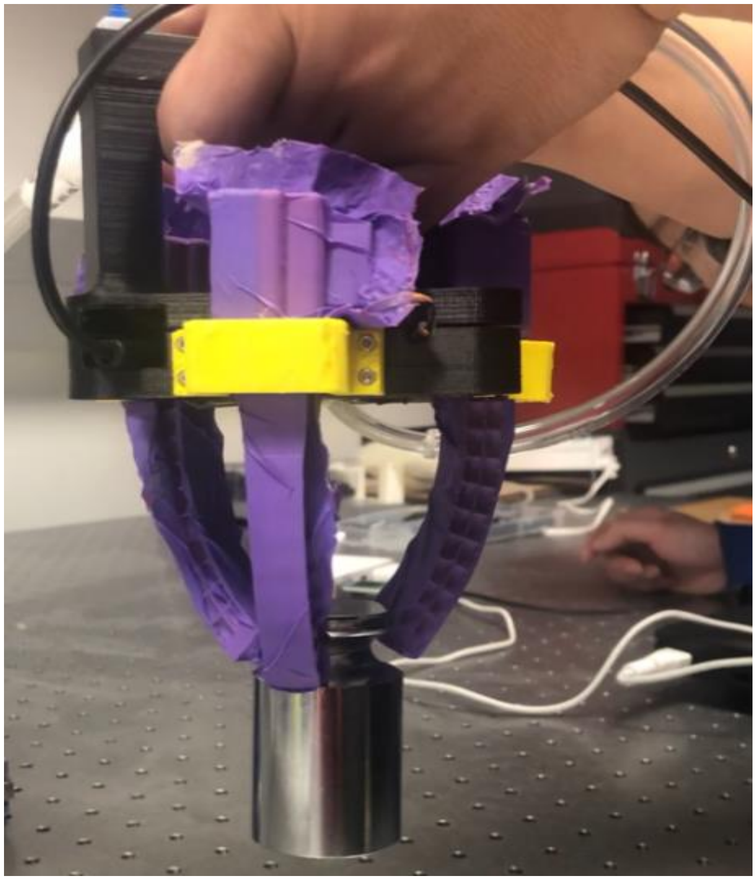


Figure 40: Lifting the 1 kg block (With Layer Jamming)

CHAPTER 6: CONCULUSION

6.1 Summary

The aim of this thesis was to design and make a working prototype of a three-fingered robotic hand which can vary its stiffness. The main goal was to combine the benefits of soft and traditional robots and show that a variable stiffness robot has the capability to do it. To do this, a variable stiffness technology and an actuation method had to be determined to vary the stiffness of the robotic hand and actuate the fingers of the hand to move from relaxed position to grasping position and then back to the relaxed position. A variety of variable stiffness technologies and actuation methods were studied, and layer jamming was selected as a method to vary the stiffness and cables to actuate the finger of the robotic hand. A three-fingered robotic hand was designed that could incorporate layer jamming and cables. A working prototype of the robotic hand was made using 3D printed parts. A stiffness test was conducted on the robotic hand, which resulted in a 60 times stiffness change. A maximum load test was also conducted which resulted in the maximum load carrying capacity to increase by 9 times when using variable stiffness. The goal of the thesis, which was the demonstration of the advantages of variable stiffness soft robots was achieved.

6.2 Future Work

The design of the robotic hand can be refined. The assembled fingers have a lot of sub parts which need to be assembled and is time taking. Different materials can be tested to make sealed bags for the fingers. A bag with a higher stiffness ratio will have the ability to carry even more load. The ends of the fingers can be fitted with a high friction material like rubber so that the robotic hand can grip slippery materials which slip through latex.

The robotic hand is a self-contained unit, which means that it does not use an external power supply for functioning and hence it is portable. However, to use layer jamming, it has to be connected to an external pump which can generate negative pressure. A micro vacuum pump can be fitted into the base of the robotic hand so that it is truly a self-contained and a portable unit.

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